Radio Science Ground Data System for the Voyager–Neptune Encounter, Part I

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The Voyager radio science experiments at Neptune required the creation of a ground data system array that includes a Deep Space Network complex, the Parkes Radio Observatory, and the Usuda deep space tracking station. The performance requirements were based on experience with the previous Voyager encounters, as well as the scientific goals at Neptune. The requirements were stricter than those of the Uranus encounter because of the need to avoid the phase-stability problems experienced during that encounter and because the spacecraft flyby was faster and closer to the planet than previous encounters. The primary requirement on the instrument was to recover the phase and amplitude of the S- and X-band (2.3 and 8.4 GHz) signals under the dynamic conditions encountered during the occultations. The primary receiver type for the measurements was open loop with high phase-noise and frequency stability performance. The receiver filter bandwidth was predetermined based on the spacecraft's trajectory and frequency uncertainties.

I. Introduction

This is the first of two articles on the Deep Space Network (DSN) implementation in support of the radio science activities of the Voyager–Neptune encounter. This article will discuss the key requirements for the implementation, but not the actual design and implementation efforts. The specifications discussed here are a combination of the *Voyager Science Instrumentation Requirements Document* (SIRD) and the DSN's requirements and goals. This arti-cle is intended as a tutorial, creating in the process a con-text in which to better present the various requirements and, subsequently, the design and implementation efforts. This article may also be useful for deriving radio science experiment requirements for future missions.

Neptune and its satellites represent the fourth plane-tary system encountered by Voyager and at least the fourth upgrade to the DSN radio science system since its initial

implementation. Consequently, the development of the requirements incorporated the considerable knowledge and understanding accumulated during past encounters. Nevertheless, the process of choosing a level of performance to be a requirement is always a bit tricky because the desired performance for the radio science instrument is open-ended; that is, the better the instrument performs, the better the scientific results will be. The scientific goals and the technology necessary to achieve them must be combined to set the actual, achievable performance. "Requirements," of course, also include a third aspect, namely, commitment, which implies a function or level of performance that is virtually guaranteed.

The Voyager radio science experiments at Neptune fell into two fundamental classes. The first class was composed of measurements related to gravity and celestial mechanics, where the gravity field is inferred from the motion of the spacecraft measured with the range and range rate using the telecommunications signals, as well as very long baseline interferometry (VLBI) and optical navigation data. This article focuses on the second class, which characterizes the electromagnetic properties of the media through which the signals pass by measuring the effects they induce on the received signal amplitude and phase. "Occultation" refers to the interruption of the light from a celestial body or of the signals from a spacecraft by the intervention of a celestial body. Occultation is also used when the media of interest fall along the line of sight between the Earth and a spacecraft. The occultation measurements form a special class of remote-sensing experiments that are unique because of the coherent nature of the probing signal. For example, in the case of stellar occultations, the signal is broadband and incoherent and, therefore, only its intensity can be used to recover information about the media being probed. In the case where a coherent signal source is used, both phase and amplitude information are available.

The radio science instrument is unique as a Voyager instrument because the ground tracking stations are part (in fact the larger part) of the instrument itself. This arrangement provides the opportunity to improve the instrument after launch. In the case of Voyager, experiments are performed using the downlink signal from the spacecraft to the Earth. This configuration has been used because it requires the least equipment on board the spacecraft. A proposal has been made for future spacecraft to place a receiver and data processor on board the spacecraft to take advantage of the 20–30 dB improvement in the signal-to-noise ratio (SNR) of the uplink-versus-downlink telecommunication signals.

II. Neptune Occultation Experiment Overview

The Voyager trajectory was chosen so that, during the course of its flyby, the spacecraft, as viewed from Earth, would be occulted by the atmosphere, ionosphere, and rings of Neptune, as well as by the atmosphere and ionosphere of Triton. In a very real sense, there were five different occultation observations. That number can, in fact, be doubled to ten because, in each case, an occultation occurs on either side of the planet or moon. A brief description of each of these different measurements follows.

A. Neutral Atmospheres

In an atmospheric occultation experiment, the S- and X-band signals from the spacecraft pass through the planetary atmosphere on their way to Earth. As they travel, they are slowed by refraction, which causes their paths to bend and increase in length relative to their length in the absence of the planet's atmosphere. The increased optical path length is essentially determined by using the signal phase as a gauge. Knowledge of the relative positions of the spacecraft, occulting planet, and Earth, as well as the gravity field of the planet, allows the bending angle as a function of altitude in the planet's atmosphere to be reconstructed from the phase data. The phase data can be inverted to recover the refractivity of the atmosphere as a function of altitude by solving an Abelian integral equation [1]. The number density of the atmosphere can be derived from the refractivity by assuming knowledge of the atmospheric constituents derived from other instruments and atmospheric models. The pressure can be derived by vertically integrating the number density multiplied by the weight of an average molecule by using the equation of hydrostatic equilibrium in which atmospheric pressure balances the weight of the atmosphere. Given both the number density and pressure as functions of altitude, the temperature versus altitude is then derived from the equation of state (the ideal gas law in the simplest case).

This process begins with the ray above the top of the detectable atmosphere. As the periapsis of the ray descends into the atmosphere, the bending-angle profile is constructed as a function of altitude, one layer at a time, until the maximum depth probed by the beam is reached. The outbound occultation is processed in time-reversed order, again beginning with the ray at the top of the atmosphere and working backward, down into the atmosphere. Therefore, the inbound and outbound occultations are processed separately. If the signal is continuously visible throughout the entire two occultations, at least one additional constraint can be placed on the atmosphere so

that the two occultation inversions match at the deepest point where their measurements overlap. This technique was used during the Uranus encounter to estimate the wind velocity in this deeper region of the planet's atmosphere [2].

Although the key measured parameter is the phase, amplitude information is available as well. The nearly exponential change of refractivity with altitude causes differential bending across the vertical dimension of the radiation pattern from the spacecraft, which causes the ray to defocus and reduces the beam's energy flux density. This, in turn, causes the amplitude of the received signal to decrease dramatically. The same effect can be used to measure refractivity. In the case of a coherent microwave signal, however, the phase is a far more sensitive measure of refractivity. Consequently, the expected defocusing of the signal level is estimated from the phase data and subtracted from the measured signal amplitude. Any residual amplitude attenuation is used to estimate the density of any microwave-absorbing constituents that might be present in the atmosphere.

The Neptunian atmospheric occultation was designed to measure the pressure and temperature of two slices through the atmosphere, over a range from approximately 0.1 millibar to several bars. Triton was expected to have a very tenuous atmosphere (if any) of tens of microbars. It was expected that the extra path length in this case would be extremely small (subcycle) and would push the limit of the technique beyond that which had previously been accomplished. It is important to note that this technique measures increased path length over the duration of the occultation. Therefore, the knowledge of the absolute distances involved is needed to a much lower accuracy than the accuracy of the *change* in path length over the duration of the occultation. A typical duration for the various planetary atmospheres encountered by Voyager was 1,000 sec, whereas the Triton occultation was expected to last only a few seconds.

B. Ionospheres

In the case of ionospheres, the electron density integrated along the signal path causes a shift in the signal phase that is inversely proportional to the signal frequency. The linear combination, S-3/11X, of the phase of the coherently related S- and X-band signals can then be formed, which cancels the nondispersive effects and leaves a quantity that is proportional to the integrated electron density, commonly referred to as the total electron content (TEC). Starting with measurements above the detectable ionosphere, the number density of the ionosphere as a function of altitude above the planet can be estimated from the differential phase data. The estimate assumes that the effect is large enough to stand out against the signatures of other dispersive effects due to instrumentation and intervening media.

C. Ring Occultations

In the case of an occultation by a ring of material, there is a modified coherent signal, as well as incoherent scattered signals, that can be received at the Earth. The amplitude and phase of the coherent signal can be used to measure the complex microwave opacity of planetary rings. The differential opacity and phase delays and the differential levels of forward scattering of the S- and X-band signals can be used to estimate the particle-size density and distribution.

Because of diffraction, the radial resolution of the opacity measurements might at first seem very coarse, as compared with the stellar occultation measurements made by the Voyager Photopolarimeter Subsystem (PPS) at infrared (IR) and visible wavelengths. Optical wavelengths are approximately 100,000 times smaller than the X-band wavelength, which makes the Fresnel scale (diffraction limit) size some 300 times larger at microwave wavelengths. However, because the microwave signals are coherent and the geometry is changing, the effects of diffraction can be largely removed in a manner similar to synthetic aperture radar, which results in a resolution of hundreds to tens of meters instead of tens of kilometers. This technique and its limitations are discussed in [3]. In addition, even with the tremendous distance between the Voyager spacecraft and the Earth, the radio science instrument has more than two orders of magnitude more dynamic range than the PPS instrument, which enables it to sense a wider range of opacities and more accurately characterize a range of opacities common to both instruments. These two opacity measurements by the PPS and the radio science instrument are, of course, complementary because of their vastly different wavelengths.

As previously mentioned, the difference between the levels of the approximately forward-scattered S- and X-band signals is used with the opacity measurements to infer the particle-size distribution and densities. The scattered signals are separated from the coherent signal by using the high-frequency resolution due to the coherence of the measurement system. In the case of Saturn's A ring, the large difference between the S- and X-band levels implied the presence of a significant number of centimeter-sized particles [4]. In the case of Uranus, the opacity at both wavelengths was large and virtually identical, which implied that the particle sizes were probably larger than either wavelength [5].

III. Key Requirements for the Instrument

The primary requirement for the instrument is to recover the phase and amplitude of the S- and X-band signals under the dynamic conditions encountered during the occultations. Data gaps are undesirable because they disrupt the continuous phase record or gauge. This happens because the spatial resolution of the key parameters depends on the signal phase measured over some finite range of time. The specifications were written so that 100-percent recovery of the data during the critical periods is highly probable.

An attempt was made to make the measurements as sensitive as possible. The fundamental performance limitations of the instrument were identified, and a goal was set to make all other sources of error as small as possible, given the constraints of available and reliable technology. As it became apparent that this goal was achievable, a set of requirements was established.

Finally, an attempt was made to enable the equipment installed at the DSN sites to meet their long-term needs. This meant improving in the ease of system operation, as well as addressing, where appropriate, the needs of future Galileo and Mars Observer experiments.

IV. Instrument Conceptual Design

As mentioned above, the instrument is made up of the spacecraft- and Earth-based microwave radio systems, which were created primarily to support telecommunications and navigation. The mode generally used for occultations is the so-called one-way Doppler mode, which is also referred to as bistatic radar. In this configuration, the S- and X-band signals radiating from the spacecraft are generated from a reference oscillator on board the spacecraft. These signals are received at the Earth and are measured there against a reference oscillator. This process differs from the "two-way" mode, where an uplink signal is generated on the ground and transmitted to the spacecraft. The spacecraft then receives the signal and uses it as a reference frequency to generate a downlink signal that is radiated back to Earth.

The advantages of using the one-way mode for an occultation experiment are two-fold. As the uplink signal passes through the intervening media before being received by the spacecraft, the spacecraft receiver (transponder) must phase lock onto the signal in order to use it as a reference from which to generate a downlink signal (which then passes through the occulting media a second time). The first problem is that the signal dynamics introduced by the occulting media make it difficult for the transponder to acquire and maintain phase lock. On the outbound atmospheric occultation, the spacecraft receiver may take up to several minutes to lock onto the uplink signal, thereby losing a significant portion of the medium under study. The second problem is that the finite bandwidth of the transponder's transfer function will filter out some of the effects of interest. This configuration does place relatively stringent requirements on the phase stability of the oscillator on board the spacecraft. The ultrastable oscillator (USO) on board the two Voyager spacecraft is the one piece of equipment specifically placed there to support radio science. For such spacecraft as Pioneer Venus, the onboard oscillator does not have sufficient stability, and the inbound atmospheric occultations are generally performed in the two-way mode. The outbound occultations are not performed in this mode because of the time necessary for the transponder to lock onto the uplink signal.

The spacecraft side of the instrument, although basically fixed, has some flexibility. The transmitting levels of the S- and X-band signals are selectable within the constraints of the available power. With Voyager, power constraints make it possible for only one of the two signals to be at high power. Another important aspect of the transmitted power is that the telemetry phase modulation can be turned off for occultations, which puts all the transmitted power into the monochromatic carrier signals. (At X-band, this meant an increase of approximately 12.5 dB in the carrier level given the planned data rates for Neptune.) Another critical function that the spacecraft must perform is an extremely important maneuver during the Neptune atmospheric occultation, where the spacecraft's high-gain antenna is pointed at the expected image of the Earth as viewed through the atmosphere. The proper execution of this maneuver places very sharp constraints on the accuracy of the trajectory prediction, as well as on the attitude control system of the spacecraft.

The ground system requires a receiving antenna with a very high gain, implying a large dish antenna. This is followed by a low-noise amplifier (LNA), presumably cryogenically cooled for optimal performance, thus creating the front end of a receiving system with a very high gain to noise temperature (G/T) ratio. This is a feature of such telecommunication systems that is critical to the SNR achievable with the system upon which the achievable telemetry rates depend. The antennas used for telemetry can be shared and serve both purposes, which should be obvious because the radio science capability emerged from the telemetry and navigation systems for deep space probes.

Because the ground receiving equipment must handle the signal dynamics induced by the planetary media of interest, the primary receiver type for these measurements is open loop. "Open loop" means that there is no signal detection in real time. The entire signal spectrum of interest is captured in real time so that the signal phase and amplitude can be detected at some later time, which allows one iteratively to optimize parameters in the detection process. The lack of real-time detection occurs because it is so difficult to detect the dynamic signals in real time, and because the optimum detection algorithm may differ from one type of occultation to another. One particular problem involves multipath, where the signal can arrive simultaneously at the Earth via multiple paths. Because the signal is essentially monochromatic, the various paths the signal takes can be separated via the unique Doppler shift associated with each path. The narrowness of the spectral line limits the ability to distinguish among different paths.

The open-loop receiver heterodynes the signal at the antenna against a series of reference frequencies derived from a common, stable, reference signal to a much lower frequency signal where it can be digitized and recorded. The frequency of the resulting downconverted signal is the difference between the received signal frequency and that of the local oscillator (LO) chain and, therefore, this frequency contains the phase noise of the local oscillators, which makes the phase stability of these LO's a critical parameter in the instrument's sensitivity. To minimize the bandwidth needed to acquire the signal, one local oscillator is tuned along the predicted Doppler profile of the received signal, which removes most of the Doppler shift prior to recording the signal. The actual bandwidth requirements will be discussed further. Recovery of the microwave signal frequency and relative phase received at the antenna require that the frequency and phase of this tunable local oscillator be recorded.

The reference frequency at the Earth receiving station is used to generate both the reference frequencies from which the LO chain is derived and the clock used to time tag the received data. Because the LO chain and, therefore, the phase stability of the downconverted signal ultimately depend on the stability of the station reference, the stability over the occultation length is critical to these experiments.

In order to fully recover the dynamic range of the received signal spectrum and avoid any further degradation of the signal when subsequent copies of the data are generated, the downconverted signals are digitized prior to recording. The digitization adds a small amount of noise to the analog signal being recorded, but this can be made negligible by using a sufficient number of bits and a stable sampling clock. The data are then recorded digitally on some form of bulk storage media (currently magnetic tapes) at the receiving site. Due to the data rates involved and the cost of transmitting the data via satellite to the Jet Propulsion Laboratory (JPL), the data are subsequently shipped to JPL within a couple weeks of the event. It is also very desirable that this media be compatible with the computer facilities of the investigators.

V. Filter Selection and Bandwidth Allocation

As discussed, one local oscillator in the open-loop receiver is tuned to reduce the required bandwidth. The narrowest open-loop filter bandwidth was selected to ensure that the Voyager signal would remain within the open-loop receiver bandwidth throughout the Neptune encounter. Figures 1 and 2 illustrate the expected Doppler and frequency rates during the encounter. The requirement was formulated after the completion of a study of the factors that contribute to frequency offsets and uncertainties at X-band.[1] There is a bandwidth requirement associated with each of the ring, atmospheric, and Triton occultation experiments at Neptune. The 3σ X-band requirements at Neptune are summarized in Table 1.

The selected filter bandwidth is the same for both frequency bands because the Doppler spread across the spacecraft antenna beamwidth is independent of frequency. The spacecraft antenna illuminates a region of the planet's rings, for example, and the resulting Doppler shift across that region results primarily from the spacecraft's motion. The Doppler shift for small angles is

$$F_{Doppler} \approx \frac{f\theta V}{c}$$

where F is the frequency of the straight-line signal to Earth, V is the component of the spacecraft velocity in the plane of the sky, c is the speed of light, and θ is the angle relative to the straight-line signal path to Earth. The maximum angle θ_{max} is limited by the beamwidth of the spacecraft antenna. Therefore, θ_{max} is inversely proportional to the frequency as

$$\theta_{max} \sim \frac{c}{FD}$$

[1] S. W. Asmar, *Signal Passband Frequency Allocation*, JPL Interoffice Memorandum Voyager-RSST-87-041 (internal document), Jet Propulsion Laboratory, Pasadena, California, October 21, 1987.

where D is the spacecraft antenna diameter, resulting in

$$F_{Doppler_{max}} \approx \frac{F\theta_{max}V}{c} = \frac{V}{D}$$

which is independent of signal frequency.

To reduce the frequency uncertainties, it was required that the receiver-tuning predictions be updated shortly before the encounter based on an improved spacecraft trajectory. Three late navigation solutions were critical for the limb-track maneuver and for determining the spacecraft arrival time. The arrival time is proportional to the frequency, and errors in it result in significant frequency errors due to the rapidly changing Doppler shift.

Factors that contributed an error greater than 1 kHz include the 1σ values of the errors listed below. These values were root-sum-squared and multiplied by 3 for the values in Table 1:

(1) Timing error: The frequency offset due to a 5-sec timing error was estimated to be 1.3 kHz.

(2) Radius error: The frequency offset due to a 50-km error in Neptune's radius was estimated to be 1.0 kHz.

(3) Ring scattering: The frequency range due to scattering by the Neptunian rings was estimated to be 6 kHz at 3 dB off antenna Earth boresight and 10 kHz at 10 dB off boresight. Though Doppler is measured on a frequency scale, the antenna beamwidth requires the same bandwidth independent of the frequency band.

(4) The Neptune Doppler uncertainty at Earth occultation ingress for an $(N - 5)$-day orbit determination (OD) cutoff date (latest estimate of late ephemeris update, LEU, see [13]) was 6.2 kHz, assuming radio-plus-optical narrow-angle information. The Neptune Doppler uncertainty at Earth occultation ingress for an $(N-2)$-day OD cutoff date (latest estimate of late stored update, LSU) was 1.0 kHz, assuming radio-plus-optical narrow-angle information.

(5) An arbitrary offset introduced to facilitate data post-processing of about 2.5 kHz was also taken into account.

(6) The bandwidth requirement for the Triton occultation was estimated to be at least 8.4 kHz. Due to the tenuous nature of Triton's atmosphere, there was no requirement for modeling the atmosphere in the tuning predictions.

Factors below the 1-kHz contribution include:

(1) Neptune's atmosphere: The uncertainties in frequency predictions in the modeling of the Neptunian atmosphere have been specified not to exceed 400 Hz by the Radio Science Team.

(2) Ultrastable oscillator: Radiation effects may cause the USO frequency to shift by as much as 50 Hz.

(3) DSP-R tuning error: The radio science predictions were expected to be generated with a frequency tuning error of less than 100 Hz. This took into account the predicted software requirements for other missions as well.

The conclusion of this study was to require the use of a 20-kHz filter as a minimum bandwidth. This was selected as a prime filter and a 45-kHz filter was required for backup. The prime filter would require a sampling rate of 50 ksps, which was an existing capability of the system used for the Uranus encounter. The backup filter would require a sampling rate of 100 ksps, accomplished by pairing up two analog-to-digital convertors per frequency band, each at a base-sampling rate of 50 ksps.

VI. Implementation Purpose

The apparent maturity of the DSN radio science system and the generally successful support to the Uranus encounter leads to a question of whether an upgrade to the ground system was needed for the Neptune encounter. The two primary reasons for the upgrade were that new capabilities were needed in the array of ground antennas and that the requirements for Neptune were tighter than those specified for Uranus.

For the Neptune encounter, the desire was to increase the receiving aperture to offset the increased distance from Uranus to Neptune. This not only implied multiple receiving antennas, but also the possibility of non-DSN observatories and tracking stations. As will be discussed, the particular array of antennas chosen included DSS 43, the Parkes Radio Observatory in Australia, and the ISAS tracking station outside of Usuda, Japan. This implied a reimplementation at Parkes (with a number of improvements), as well as an entirely new implementation in Japan.

The Neptune requirements were tighter than those of the Uranus encounter for two basic reasons. The first reason was the closer and faster flyby of Neptune, which increased the Doppler rates and the requirements on the

support system's ability to provide prediction updates very close to the time of closest approach. The second requirement was based on tightened performance specifications, particularly in the area of phase stability, to avoid problems experienced during the Uranus encounter. A serious problem occurred at Parkes when the phase stability of an LO seriously degraded the Parkes data's ultimate utility. Another dramatic problem was the very late deletion of the DSS 42 X-band receiver channel from the Uranus radio science array due to problems of coupling between the DSS 42 and 43 IF signals within the receiver. Better specifications for the necessary system performance and tighter performance requirements resulted from these problems as well as the justification of the implementation of special equipment designed to test the system at the level of those requirements. Very limited capabilities had previously been provided and their development, along with a testable set of performance specifications, played a major role in the ultimate success of the implementation.

Reliability had always been a concern of these implementations and this encounter was no exception. Because this encounter was probably the only time that Neptune would be viewed up close for another 20 years, system reliability was considered to be crucial. The stated Voyager SIRD specification was 99 percent probability of 100 percent data collection over any four-hour time span. That specification was not formally accepted by the DSN because of the virtually untestable nature of the requirement for at least 500 such tests with only a single allowable failure. Even though the formal requirement was not accepted, the purpose of the requirement was understood and led to a design with virtually 100-percent redundancy throughout the entire ground array.

In addition, from a longer term DSN perspective, there was a strong desire to improve the operability of the system for multimission support, which would ultimately lead to better the system reliability and human operator interaction. That desire led to a series of improvements in the monitor and control aspects of the system.

VII. Arraying Selection and Expected Performance

The purpose of using an array of ground antennas for the reception of the radio occultation data was three-fold. The first was to improve the SNR of the received S- and X-band signals. A major fraction of the SNR reduction relative to Uranus was compensated for by the increased aperture and efficiency of the DSN 70-m antennas. The second purpose was to provide redundancy so that if an antenna failed, other antennas would continue to acquire critical data. The third purpose was to separate effects of interest from those due to instruments. Multiple receiving sites would allow isolation of effects unique to a particular site.

The array for Uranus differs from the Neptunian telemetry array in two ways. First, the arraying is done at microwave frequencies, as opposed to video-band modulation signals. Second, the signals are combined after the acquisition is complete, as opposed to the real-time combining by the telemetry array. Real-time combining was due primarily to the dynamic nature of these signals, which made near optimal real-time combining virtually impossible. There are, therefore, no requirements for high-rate real-time data communication links, which is important because the data rates are on the order of 800 kbps. Playback of certain portions of the data was required for quick-look analysis immediately following the encounter.

In selecting the antennas nominally desired to take part in the array, the following factors were considered:

(1) The expected use of at least one DSN 70-m antenna

(2) The 5.5-hour separation between the Neptune and Triton events

(3) The desire for reception at high elevation angles to reduce noise temperature and the amount of Earth atmosphere and ionosphere through which the signals had to pass

(4) The desire to utilize the SNR improvements made for the telemetry array

(5) The desire to use a few large antennas to reduce complexity and level of effort

(6) The capability to array both S- and X-band signals

Given the desire for reception at high elevation angles and the −22-deg declination of Neptune at the time of encounter, the most desirable DSN 70-m antenna was DSS 43. As shown in Fig. 3, the entire set of events at Neptune and Triton could be received at this one location at relatively high elevation angles near 45 deg. Such reception was also desirable because the gain of the DSN 70-m antennas peaks in this range, which also allows use of the Parkes radio telescope—already a part of the telemetry array with DSS 43 and with approximately the same elevation angle coverage as DSS 43. Parkes had been outfitted as an X-band–only receive site for the Uranus encounter and was expected to be in the same configuration for the Neptune encounter. Parkes, with the lack of S-band telemetry-arraying requirements, combined with

its small cage at the prime focus of the antenna housing the LNA's and first downconversion stage of the receiver, was expected to fulfill the minimum needs of the three arraying functions at X-band, but not of those at S-band.

Japan is located approximately at the same longitude as Parkes, and the Japanese space agency, ISAS, had built a 64-m tracking station in Usuda, Japan, to provide S-band tracking of its two spacecraft, Suisei and Sakegake, which encountered Halley's comet in 1986. With the use of a cryogenically cooled S-band LNA, the Usuda antenna had demonstrated a G/T comparable to a DSN 64-m antenna [6] and had been used in the past both to track ICE, a National Aeronautics and Space Administration (NASA) satellite, and support the space VLBI experiment with the Tracking and Data Relay Satellite System (TDRSS). Usuda's ability to track at S-band potentially fulfilled the S-band arraying needs with a G/T nominally within 1 dB of DSS 43. It had the disadvantage of being located at a 36 deg north latitude, which caused the encounter events to occur at approximately a 20-deg elevation, but both the Neptune and Triton occultation events would be visible from a single site. Given these considerations, the nominal array was defined as DSS 43 operating at both S- and X-band, Parkes operating at X-band, and Usuda operating at S-band. The desire for both Parkes and Usuda to operate at both S- and X-band was also stated.

The expected array performance relative to Uranus is summarized in Table 2. The G/T for DSS 43 was to be improved over that at Uranus by 1.9 dB at X-band and by perhaps 1.4 dB at S-band, with the extension of the antenna to 70 m in diameter. The Parkes radio telescope performance was to be the same as that at Uranus, which meant that its G/T would be about 3 dB less than that of DSS 43. The Usuda S-band performance was expected to be within about 1 dB of that of DSS 43. Usuda has less area but a higher efficiency and a lower zenith noise temperature, and also a lower elevation angle because of its northern latitude location. Table 2 also includes the approximately 2-dB loss in received X-band signal level at DSS 43 due to a mispositioned subreflector during the Uranus encounter.

The lower S-band noise temperature at Usuda was partially due to the assumption that DSS 43 would have its diplexer in place to allow uplink operations during the encounter pass. As it turned out, because of clever planning by the Voyager Radio Science Team, uplink was not required from DSS 43 and the diplexer was not used, which lowered the system noise temperature (SNT) from 20 to 16 K, an improvement of 1 dB in SNR. Removing the

diplexer also reduced Usuda's SNR to about 2 dB below that of DSS 43 and the improvement at S-band over that of DSS 43 alone to about 2.1 dB, or a 21-percent reduction in root-mean-square (rms) amplitude and phase jitter.

The importance of the redundancy provided by such an array cannot be overstated. In the event of a failure of any of these three antennas, a dual frequency data set would continue to be collected at the other two sites. DSS 43, of course, would be the greatest loss because of its higher SNR and dual frequency capability. However, Parkes and Usuda would essentially combine to produce individual S- and X-band data sets equivalent to those acquired at a DSN 64-m station. In addition, either DSS 45 or 42 could be used with a reduced SNR, particularly to produce the dual frequency data sets for characterizing the ionospheres of Neptune and Triton. The redundancy also made the data-acquisition process less susceptible to local weather effects, a serious concern during August in Australia.

VIII. General Stability Discussion

The SNR, as well as the phase and amplitude stabilities of the received signal, is extremely important to the sensitivity and accuracy of the parameters ultimately extracted from the received signal phase and amplitude. The effect of the SNR is to add a random phaser to the signal phaser modulating the phase and amplitude of the signal. For SNRs greater than approximately 10, the total noise power of the random phaser is statistically equally distributed between the amplitude and phase, which makes the amplitude and phase noise power spectral densities each half of the total power spectral density. The thermal noise associated with the SNR is also white or uncorrelated from sample to sample, assuming that the measurement noise bandwidth is the reciprocal of the sample interval. The implications for the different types of occultation measurements are briefly discussed below.

A. Atmosphere

The SNR is a dominant source of error in the estimates of temperature and pressure of the upper regions of the atmosphere, which was very important in the case of Triton because of the tenuous nature of its atmosphere. The SNR is also important deep in the atmosphere because of defocusing, which causes a loss in the signal level, typically at least 20 dB for the Voyager occultations. The actual defocusing effects on the intensity scales as a parameter M, which for an isothermal atmosphere equals $[1 + (\alpha D)/H]^{-1}$ where α is the bending angle in radians,

D is the distance from the spacecraft to the limb, and H is the refractivity scale height [7]. At the deepest point in the Neptune occultation, the expected values for α, D, and H were approximately 15 deg, 40,000 km, and 25 km, respectively, which resulted in an expected intensity reduction of 400 or 26 dB. The need for an even higher SNR exists when there are small-scale, vertical structures in the atmosphere, such as cloud decks, with small refractivity scale heights, where refractivity changes more rapidly with altitude than the background atmosphere. Such was the case with Uranus and was anticipated (correctly so) at Neptune. The scale height in these regions can be a factor of 10 smaller than the background atmosphere, which increases the defocusing in the region by a factor of 10 or more. Signal multipath is typically associated with these regions as well. Each of the multipath signals passes through a unique vertical region of the atmosphere and must, therefore, be recovered to characterize the atmosphere at and below this depth.

The SNR necessary for tracking signals passing deep into the atmosphere can be estimated as the minimum SNR needed for signal detection after accounting for the expected signal level loss due to atmospheric defocusing and absorption. The minimum SNR must also account for the noise bandwidth equivalent to the signal detection-integration interval. The minimum SNR needed for detection is typically taken to be 10 dB. The maximum integration time for detection is generally taken as the time for the signal to descend a Fresnel scale, F, the diffraction-limited vertical size of the geometric ray. In the upper atmosphere, where bending is insignificant, the Fresnel scale is $\sqrt{\lambda D}$, where λ is the wavelength and D is the distance from the spacecraft to the planet's limb. This descent time is the Fresnel scale divided by the component of the spacecraft velocity in the direction of local vertical at the deepest point of the ray in the atmosphere. In the case of Voyager, this leads to approximate X- and S-band integration times of 0.08 and 0.16 sec, respectively, at the top of the atmosphere. However, deep in the atmosphere, both the vertical dimension of the Fresnel scale and the vertical descent rate of the ray decrease due to bending. The vertical dimension of F scales as $\sqrt{M}$, whereas the velocity scales as M, which causes the integration time to scale as $1/\sqrt{M}$ and the associated noise bandwidth as $\sqrt{M}$. The minimum free-space SNR can then be estimated as

$$SNR_{0\ FS} = \frac{10V_v\sqrt{M}}{FM} = \frac{10V_v}{F\sqrt{M}}$$

where $SNR_{0\ FS}$ is the free-space signal-to-noise-spectral density ratio, V_v is the vertical component of the space-craft velocity relative to the planet, and F is the geometric Fresnel scale at the limb of the planet in the absence of atmosphere.

The factor of 10 in the numerator is the minimum SNR required for reliable signal detection. In the case where $M = 1/400$, $SNR_{0\ FS}$ should be at least 34 and 31 dB for X- and S-band, respectively.

Another item of interest is the characterization of absorbing material present in the atmosphere. Ammonia, a very common solar system constituent, absorbs more at X-band wavelengths than at S-band, which causes one to consider selecting the highest available transmitter power at S-band if the presence of ammonia is indeed anticipated. Ammonia was not expected in the Neptunian atmosphere at the depths that were probed by the radio signal, based on the Uranus experience, and the X-band transmitter in the high-power mode was selected as the optimum configuration. This assumption, in fact, proved to be incorrect, and ammonia was indeed present in sufficient quantities to cause the S-band signal to be detectable deeper in the atmosphere than the X-band signal despite an ~15-dB higher X-band free-space SNR.

Amplitude stability over time scales long enough to allow effects other than the SNR to become significant is also important for characterizing microwave-absorbing material in the atmosphere. The sensitivity to and accuracy of recovered absorption constituent number densities depend on instrumental amplitude stability. Typically, one looks for differential absorption between the S- and X-band signal levels because the absorption strongly depends on wavelength. Knowledge of the actual pointing of ground and spacecraft antennas during the observations becomes very important because the antennas are an obvious source of relative changes between S- and X-band signal levels in as much as antenna beamwidth scales with wavelength.

Instrumental phase stability sets limits on the accuracy of the recovered atmospheric temperature and pressure profiles. In the extreme case, the phase can be sufficiently unstable that the atmosphere cannot be separated from the phase noise. The transmitted signal frequency and phase during an occultation are unknown and must be estimated from the frequency measured just prior to the occultation interval. Given that the phase error in this estimate does not increase too rapidly over the time scale of an occultation, the phase uncertainty sets the upper altitude limit at which a specific temperature accuracy can be achieved. As the ray descends deeper into the atmosphere, the temperature error tends to decrease because

the changing path length increases exponentially with decreasing altitude and generally much faster than the uncertainty in the phase change of the system, particularly of the oscillators involved. A relevant time scale is the time it takes the periapsis of the ray to descend one scale height in the atmosphere. A scale height is the altitude change over which the atmospheric parameter, such as density or pressure, changes by e. In the case of Neptune, with an approximate scale height of 25 km, that time was about 3 to 4 sec in the upper atmosphere.

B. Ionosphere

The ionosphere is characterized by measurements of $\phi_S - 3/11\phi_X$, the differential phase between S- and X-band signals. The effect of SNR on this measurement is dominated by the S-band SNR because of the combination of the 3/11 scaling factor for the X-band and the 15-dB higher X-band SNR. As shown in the following equation, the S-band SNR makes the S-band responsible for more than 99 percent of the high Fourier frequency noise:

$$\sigma_{\Delta\phi}^2 = \sigma_S^2 = \left(\frac{3}{11}\right)^2 \sigma_X^2$$

$$\cong \sigma_S^2 + \left(\frac{3}{11}\right)^2 10^{-1\,5}\sigma_S^2$$

$$\cong 1.0024\sigma_S^2$$

This is important in relatively short-term time scales, typically less than 10 to 100 sec, depending on the magnitude of the Earth's ionosphere and interplanetary media-induced instabilities. Thus, for events that occur relatively quickly, such as small-scale vertical structures in the ionosphere, it is very important to maximize the S-band SNR. This is also true in terms of spectral density because layers in the ionosphere will induce multiple signals analogous to those described in the neutral atmosphere, and it is desirable to recover all the signals to recover the complete vertical profile of the ionosphere.

It is worth noting that this effect is very important in the removal of ionospheric effects, for instance, in the neutral atmospheric occultations. If, for example, the ionospheric effects are estimated and subtracted from the X-band neutral atmospheric data over time scales where this SNR effect is important, a tremendous increase in the short-term jitter of the X-band phase data will result by adding in phase noise from the lower SNR S-band signal. This effect must be considered before applying the ionospheric correction because in terms of ultimate measurement sensitivity, this cure may be worse than the problem.

For time scales greater than 10 to 100 sec, the S-3/11X-band phase is limited both by the equipment and any dispersive media between the Neptune system and the ground-based receivers. Media calibration is therefore very desirable, if available at a sufficient level of accuracy. In addition, in the case of neutral atmospheric occultations, the signal passes through the ionosphere on its way into and out of the neutral atmosphere, which underscores the importance of separating dispersive ionospheric phase shifts from neutral atmospheric effects when measuring the ionospheres of Neptune and Triton.

C. Rings

The SNR sets limits on both the minimum and maximum measurable opacities, as well as on the uncertainty associated with the measurements. The smallest measurable effect is limited by jitter in the signal amplitude associated with the SNR. The largest measurable opacity is limited to the point when the coherent signal can no longer be detected. In practice, the radial resolution of the diffraction correction process is typically reduced to increase the SNR and decrease the opacity uncertainties to more useful levels [3].

The SNR is also extremely important in determining the measurement sensitivity of the nearly forward-scattered signals that are combined when available with the coherent signal opacities to place limits on particle-size distributions and densities. The forward-scattered power is incoherent and occurs over a small range of frequencies shifted relative to the direct coherent signal due to a combination of the spacecraft and ring particle velocities. To detect this power, the scattered signal power spectral density must be higher than the receiver thermal noise spectral density. This is important at both S- and X-band frequencies because differential forward scattering power places constraints on the particle sizes. This effect was not expected to be detectable at Neptune, but was also not expected at Uranus and was indeed present although not fully understood [5].

One of the main objectives of these occultations is to measure the radially dependent microwave opacity. As previously mentioned, because the signal is coherent, the diffraction effects can largely be removed, which results in ~10-to-100-m level resolution, depending on occultation geometry. There are numerous effects limiting the ultimately achievable resolution, including navigation errors, spacecraft antenna beamwidths, SNR, knowledge of the geometry, and the coherence time of the measurement system.

In the diffraction removal process, the rings are treated as an azimuthally symmetric diffraction grating depending only on radial distance from the planet. The phase length of a signal traveling from the spacecraft through a particular ringlet and then to the Earth is known so that the signal phase associated with this ringlet can be estimated as a function of time. This phase pattern can then be correlated against the received signal spectrum to detect the complex opacity of the ringlet. The opacity is complex because it potentially alters both the phase and amplitude of the signal passing through it, and because the ability to perform the matched filter technique depends on the time span over which the oscillator's phase is coherent. Eventually, over a sufficiently long time span, the oscillator's phase will gradually lose coherence, which causes the model and data to become uncorrelated and to set a maximum time span over which the phase matching process will work. In [8], an approximate relationship between coherence time and Allan deviation is used to derive a simple and general relationship between the oscillator's stability and the limitation that it places on the resolution of the recovered opacity profiles. A more rigorous and exact analysis for the case of a white-noise frequency oscillator has been given in [7].

For the reasons already given, where possible, it is desirable that the measurement-system phase-noise spectral density not degrade the SNR. Again, a case in point pertains to the data taken at Parkes during the Uranus encounter. Phase noise was discovered in the Parkes data set within a few hertz on either side of the carrier, with a much higher level than the continuous thermal phase noise. The additional phase noise reduced Parkes to a much less effective antenna and rendered it virtually useless from the point of arraying phase information. The source of the problem was subsequently isolated to be a noisy multiplier in the first local oscillator of the receiver. Since the amplitude of the LO was unaffected by this frequency multiplier, the amplitude spectrum of the downconverted signal in the Parkes data set had the full sensitivity of the G/T of the antenna and was, in fact, combined with the DSS 43 data, which provided a 1 to 1.5 dB improvement in the SNR.[2] This, of course, also points out the importance of the amplitude noise spectral density.

Systematic modulation of the signal created in the process of the reception can create apparent systematic patterns in the diffraction-corrected radial opacity profiles, a fact also discovered during processing of the Uranus data acquired at Parkes. The Parkes problem at the Uranus

[2] L. Tyler, personal communication, Jet Propulsion Laboratory, Pasadena, California, 1987.

encounter led to tighter specifications on spurious signals in the receiving systems.

The longer term amplitude stability is particularly important for detection of the presence of tenuous rings and for comparing measurements of the same ring on either side of the planet. The ability to associate a dip in the received signal level as a feature in the occulting media depends directly on the instrument's gain stability. This technique again demonstrates the importance of multiple receiving sites that allow determination of whether the effect is common in multiple data sets.

IX. Phase-Stability Characterization

A significant advance in the preparations for the Neptune encounter was the characterization of the phase-stability requirements in terms of statistical figures of merit used in the frequency and timing world. Using Allan variance and phase-noise spectral density (also referred to as spectral purity), the entire range of time scales of interest from 10 kHz on either side of the carrier to integration times of 1000 sec can be specified. The use of standardized figures of merit developed out of stability requirements late in the implementation efforts for the Uranus encounter and the preparations for the Galileo gravitational wave search experiment, which allowed stability error budgets to be created and clear design trade-off decisions to be made. Systematic testing of the performance of the various assemblies, subsystems, and systems against the required performance was also made possible.

The Allan variance was used to cover time scales of 1 sec and greater. The Allan variance provides no information on the absolute accuracy of the frequency of a signal, but does characterize its fluctuations over various time scales [9]. Since the radio occultation experiments primarily involve relative changes in phase and phase rate over a certain range of time scales, the Allan variance is an appropriate statistic. It also has the advantages of being simple to calculate and of converging for most types of noise encountered in these systems.

The spectral density of phase noise was used to characterize phase-stability performance over subsecond time scales. Specifically, performance was specified in terms of the single sideband phase noise, $S_\phi(f)$, over the range from 1 Hz to 10 kHz away from the carrier. The same level was used to specify the level of any spurious signals relative to the carrier signal level as well as the spectral density of

amplitude noise that was used to characterize the subsecond fluctuations in the signal amplitude. The long-term fluctuations of signal amplitude are relatively constrained as compared with signal-phase fluctuations. Therefore, a figure of merit that filters out the long-term fluctuations in determining performance over a range of time scales, such as the Allan variance, was not required, and a regular variance was used to specify amplitude performance.

The actual phase-stability requirements for the encounter were set with the idea that the stability of the received signal should be limited by the combination of the spacecraft USO, the propagation noise imposed by the intervening media, and the telecommunications link performance. The phase noise inherent in the downconversion process of the ground receiving system was to be essentially negligible as compared with the three sources of noise mentioned above. This goal was technically feasible partly because the USO was a 15-year-old crystal oscillator and better oscillators had since become available and partly because the distance to Neptune was so great that the received SNR was relatively low. "Essentially negligible" phase noise was chosen to mean 10 dB or more below the noise-power spectral density inherent in the link—a value chosen because a 10-percent increase in power increases the rms by a factor of only 5 percent and because it was committable as a guaranteed level of performance.

For stability characterizations using amplitude rather than power, such as the square root of the Allan variance or Allan deviation, the margin was chosen to be 3, or approximately the square root of 10. The USO stability[3] and the corresponding system stability requirement, as characterized by the Allan deviation, is shown in Fig. 4. At 10 sec, performing a root sum square on the USO and system performance yields a combined Allan deviation of 1.044×10^{12}, or a degradation of 4.4 percent of the typical stability of the USO.

In the case of phase-noise spectral density, the signal at the output of the LNA was limited by a combination of the USO and the thermal phase noise resulting from the finite SNR. The estimated single-frequency performance and Voyager requirements are shown in Fig. 5. The maximum frequency of 10 kHz was chosen because the bandwidth of the receiver output was 20 kHz. The estimated stability of the received X-band signal is labeled VGR-N X-band 70 m, and it represents the combined limitations

[3] S. W. Asmar and P. M. Eshe, *Evaluation of the USO Performance—Final Report*, JPL IOM Voyager-RSST-90-121 (internal document), Jet Propulsion Laboratory, Pasadena, California, January 17, 1990.

of the X-band SNR and the Voyager USO. The overall X-band system performance was constrained to the levels labeled VGR-N X-band Requirement. The required S-band performance is less stringent than that of the X-band because of lower S-band SNR levels. Additionally, primarily due to cost, the hydrogen maser modifications were specified to meet the estimated Mars Observer requirements labeled as DSN Post-1989 X-band Requirement.

X. Coherent Arraying Requirements

In order to array two signals with near optimum combined SNRs, the relative phase difference between the two signals must be held within a small fraction of a cycle. This relative phase difference will drift because of the finite phase stability of the measuring systems as well as media effects along the different signal paths to each antenna on the Earth. The phase instability of the USO is common and, therefore, will not affect the relative phase difference. The desire is to hold the relative phase within this bound for as long as possible. In the extreme case, the ability to "blindly" array the signals received at two different antennas must be possible over the atmospheric occultation period. The need for this level of stability was driven by the possibility that the occulted S-band signal might be difficult, if not impossible, to detect upon reception at a single station, but the combined data would sufficiently increase the SNR to provide a reliable detection. The Allan variance is a relevant figure of merit for the stability required in this case.

One method of maintaining a small phase difference between received signals is to simply perform a linear phase extrapolation based on the measured phase difference in the past. One begins with the measured phase, at a time, τ, ago and runs a straight line through it and the measured phase at the present time. The error in the extrapolated phase estimate at a time, τ, in the future is related to the Allan variance as follows:

$$\sigma_{\phi\ ext} = \sigma_y(\tau)\sqrt{2}\tau F_0$$

where $\sigma_{\phi\ ext}$ is the rms of the extrapolated phase error in cycles, σ_y is the Allan deviation, and F_0 is the nominal downlink frequency. A similar argument can be made in the case of a simple linear phase interpolation where the phases at the beginning and end of an interval are known, but the signal phase is unknown within the interval corresponding to the situation case of an occultation. In this case the error in the phase estimate at the center of the interval can be shown to be:

$$\sigma_{\phi \ int} = \frac{\sigma_y(\tau)\tau F_0}{\sqrt{2}}$$

where the interval length in this case is 2τ. As mentioned, the maximum interval of interest was approximately 2,000 sec, which covered the length of the Neptunian atmospheric occultation. Guaranteeing a phase error of less than 0.1 cycle at the center of this interval implies an rms phase error, $\sigma_{\phi \ int}$, equal to 0.03 cycle. The equivalent σ_y at S-band would be about 2×10^{-14}. An analogous X-band number would be 5×10^{-15}. These are tight specifications relative to the performance and were treated as goals rather than as requirements.

Another useful aspect of these relationships is the determination of the duration over which the phase difference can be predicted with sufficient accuracy for arraying. It is particularly important to avoid adjusting the received phase over time scales where the signal phase contains relevant information. Measurement of small changes in the received signal phase caused by ringlets is a particular example. In that case, the coherent signal detection interval can be as long as the coherence time of the oscillators involved, which, in the case of Voyager, is approximately 100 sec at X-band.

XI. Differential S- Versus X-Band Phase Specifications

The actual S- versus X-band performance of the spacecraft radio frequency (RF) system is unknown since it was not measured with sufficient accuracy prior to launch. The RF system is presumed to be very stable due to its design and the relatively benign environment in which it resides.

An estimate of the interplanetary effects can be found in [10] where an extended span of dual frequency Viking data was used to estimate the range of phase instabilities caused by the interplanetary solar wind. The results indicate that the Allan deviation of the S-3/11X phase observable at the Voyager–Neptune encounter Sun–Earth–probe angle of ~127 deg ranges from about 3×10^{-14} to 2×10^{-13}.

Before choosing a specification, the needs of other spacecraft should be considered. The accuracy goal of the Galileo Faraday rotation experiment, which measures the difference between the orthogonal circular polarization components of the linearly polarized Galileo S-band downlink, is approximately the same value. The Faraday effect is caused by a combination of the magnetic field and electron density, requiring the S-3/11X phase measurement to characterize the electron density and allow recovery of the magnetic field from the differential S-band phase data.

The gravitational wave search experimenters also desire knowledge of the TEC in order to remove its effects from the signals, thereby improving instrument sensitivity. For the Galileo X-band uplink experiment, scheduled possibly as early as 1993, during the joint opposition with Mars Observer, measurements of the electron density using S-3/11X phase of the downlink can be used to reduce the plasma effects at least on the X-band downlink signal and possibly the uplink signal as well. The effect at opposition can potentially be as little as 2×10^{-14} at 1000 sec at S-band. The corresponding effect on the X-band downlink would be about 1.5×10^{-15}, which is a substantial portion of the 5×10^{-15} stability requirement on the entire X-band uplink and downlink system, so it is desirable to be able to accurately measure it and remove its effects at least from the downlink. An S-3/11X measurement accuracy of 6×10^{-15} would allow calibration of the X-band downlink to a level of 5×10^{-14}, which would make it negligible in the system stability error budget.

The actual Voyager specification on the S-3/11 X phase drift of the receiving equipment was 1 deg rms over 1000 sec,[4] approximately equivalent to 1×10^{-15}. This was an old specification inherited from previous specifications, but never formally tested. In comparison with the interplanetary noise just described, it appears unnecessarily tight, but the open-loop receivers are designed for excellent common mode noise cancellation when the S-3/11X combination is formed. Therefore, the requirement was tentatively accepted because the system was expected to perform approximately at this level.

The total spectrum of system performance from 1 to 1000 sec is actually limited by the S-band SNR over the shorter time scales and by media noise over longer time scales, with a transition region in the 10 to 100 sec region, depending on the level of the media noise. This specification, reflecting both types of noise, is shown in Fig. 6.

XII. Antenna-Pointing Requirements

The basic desire for antenna pointing was to maximize the antenna gain over the period of interest without introducing significant phase and amplitude perturbations. Due to its unique location and mechanical design, each of the three antennas had a range of elevation angles over which the Neptune events would occur and a particular

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maximum gain versus elevation angle curve of potential performance. The requirement for antenna-gain performance and, therefore, for pointing accuracy was that the antennas should point accurately enough so that their actual gain would be within 0.5 dB of their maximum potential gain as a function of elevation angle. A tighter requirement would have been desirable, but not practicable. In the interest of separating amplitude effects due to the antenna from those due to occulting media, a specification was also written that required the reconstructed antenna gain to be accurate to 0.1 dB.

A constraint that must immediately be considered is that the antenna pointing must be performed without aid of a signal feedback mechanism because of the dynamic nature of the received signal's amplitude and phase during occultations. The lack of feedback is significant because the DSN normally conically scans the antenna boresight around the direction of the spacecraft and uses the signal amplitude changes to keep the antenna on point once the signal is acquired.

The signal's optical path length through the antennas is significant. Path length changes due to the antenna were to be far less than the effects of interest. Phase shifts as small as 10 deg were apparent in the X-band data taken during the ring occultations at Uranus [5]. The phase shift is equivalent to a path length change of 1 mm, which resulted in a goal to understand any path-length changes in the antenna of 0.1 mm. The time scale of these ring effects is about 10 sec or less, which created a relatively tight specification of 3.3×10^{-14} over 10 sec at X-band. In reality, a requirement could have been set a factor of three higher and could still have kept within the total system stability specification of 3×10^{-13} over 10 sec. Relatively quick changes in path length are the real source of concern. A 0.1-mm change over 100 sec or more would never be apparent because of other sources of phase error.

An additional operational goal was the removal of the need for any special pointing calibrations. Normally, the subreflector position changes with time to keep the subreflector at the antenna focus as the pointing angles change. In the pointing mode chosen for the Uranus encounter, the subreflector position was fixed in all axes. Among other reasons, this was done to avoid any sudden path-length changes. While this strategy seemed to be safe and conservative, it resulted in a pointing offset relative to the standard spacecraft tracking mode, which made the standard pointing offset tables unusable and required special calibration tracks to generate the special offset tables. The multiple offset tables caused operational confusion. The subreflector positioning strategy ultimately used for

the Neptune occultation events allowed the subreflector to move along the Y-axis (effective elevation angle), which not only removed the need for special calibration tracks, but also introduced less path-length change than fixing the subreflector in all axes [11].

XIII. Follow-On Noise Temperature

Because the G/T of a deep-space receiving system is a very precious commodity, a goal was set that the elements in the receiving system following the LNA should degrade the front-end system temperature by no more than one percent. Given a front-end system temperature of approximately 20 K, this is equivalent to about 0.2 K in noise temperature. The primary sources of noise were identified as the receiver and the digitization process.

The receiver has a certain amount of inherent loss in transporting the signals over the long distances from the antenna front-end area to the control room. The receiver must also provide a sufficient gain from the levels at the LNA output to drive the analog-to-digital converters (ADC's). The additional requirement was set so that the noise of any amplifier stage in the receiver would be at least 23 dB below the amplified front-end noise at that stage of the receiver.

In the case of the signal digitization prior to recording, the resolution of the ADC used to digitize the down-converted signal can be determined by the requirement that the quantization noise be at least 23 dB below the front-end noise level at the receiver output. Taking the X-band signal-to-noise spectral density ratio to be 46 dB and the minimum final filter passband to be 20 kHz, or about 43 dB relative to 1 Hz, the total SNR of the down-converted and filtered signal would be $46 - 43 = 3$ dB.

To demonstrate the effect of the quantization noise, take an ADC with N bits of resolution resulting in 2^N levels equally spaced across the full-range voltage, FR, of the ADC. Next, assume that the quantization error is uniformly distributed from $-1/2$ lsb to $+1/2$ lsb, where an lsb is a least significant bit and equals FR divided by 2^N. This is a safe assumption, given that the front-end noise is well above that of the ADC quantization error, which is the goal. This assumption leads to an rms error of quantization noise of $\text{lsb}/\sqrt{12}$. In terms of its full range, the quantization rms noise level is then $FR/(2^N\sqrt{12}) = FR/(2^{N+1}\sqrt{3})$. If the input to the ADC were a sinusoid signal with amplitude, A_s, equal to half the full range of the ADC, the signal would just fit within the ADC's voltage range. The rms voltage of the sinusoid

would be $A_s/\sqrt{2}$ or $FR/2\sqrt{2}$. If the input sinusoid had a finite SNR equal to σ_S^2/σ_N^2, the noise power of the input could also be expressed in terms of FR. For example, an SNR of 3 dB, the approximate X-band SNR in a 20 kHz bandwidth, results in $\sigma_N^2 = \sigma_S^2/2 = FR^2/16$. In reality, the input signal amplitude would never be set at the limits of the ADC because any additional noise would cause the input waveform to be clipped. To reduce the probability of clipping to an insignificant level, the input signal is attenuated by a factor of 16, which makes the input noise power equal to $FR^2/256$ or $FR^2 \times 2^{-8}$. The ratio of the input noise to the quantization noise becomes

$$\frac{FR^2 \times 2^{-8}}{FR^2/(3 \times 2^{2N+2})} = 3 \times 2^{2N-6}$$

Maintaining this ratio above 200 (23 dB) implies that N must be greater than 6. In fact, the ADCs of the existing system have 8-bit quantization, which results in an SNR increase of 0.03 percent, or 0.0014 dB, and which meets the "negligible" criterion.

XIV. Conclusion

The requirements for the radio science ground data system for the Voyager–Neptune encounter were developed based on experience with the system's performance at previous encounters, the unique geometry and configuration at Neptune, and the need to accommodate an array of three Pacific-basin ground stations. The specifications were derived from the Voyager Project's *Science Instrumentation Requirements Document*, as well as the DSN goal to accommodate, where appropriate, requirements for future missions. For the occultation experiments addressed here, the key requirement was acquisition of the spacecraft signal spectrum of interest in a phase-continuous manner with minimal degradation under dynamic conditions. This acquisition was accomplished by using open-loop receivers with excellent phase and frequency stability. The requirements discussed here emphasize the importance of system stability as defined in a clear set of specifications against which the system could be tested and the relation of stability to the ultimately derived quantities to characterize the Neptune system.

Acknowledgments

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Table 1. Bandwidth allocation requirements

Radio source	Using LEU, kHz	Using LSU, kHz
Ring scattering	31.1	15.5
Atmosphere	21.8	8.4
Triton	29.5	13.9

Table 2. Signal-to-noise ratio comparison relative to DSS 43 64-m performance at Uranus encounter

	X-band, dB	S-band, dB
70-m extension	1.9	0.8
Antenna pointing[a]	2.0	0.2
Listen-only mode	—	1.0
Parkes [12]	−1.0	—
Usuda	—	0
Array at Neptune[b]	6.3	4.1

[a] Due to DSS 43 antenna-pointing problems with the subreflector during Uranus encounter, degradation was −2 and 0.2 dB at X- and S-band, respectively [14].
[b] Improvement in the SNR due to the Parkes/DSS 43 (70-m) and Usuda/ DSS 43 (70-m) arrays relative to DSS 43 alone at 64 m.
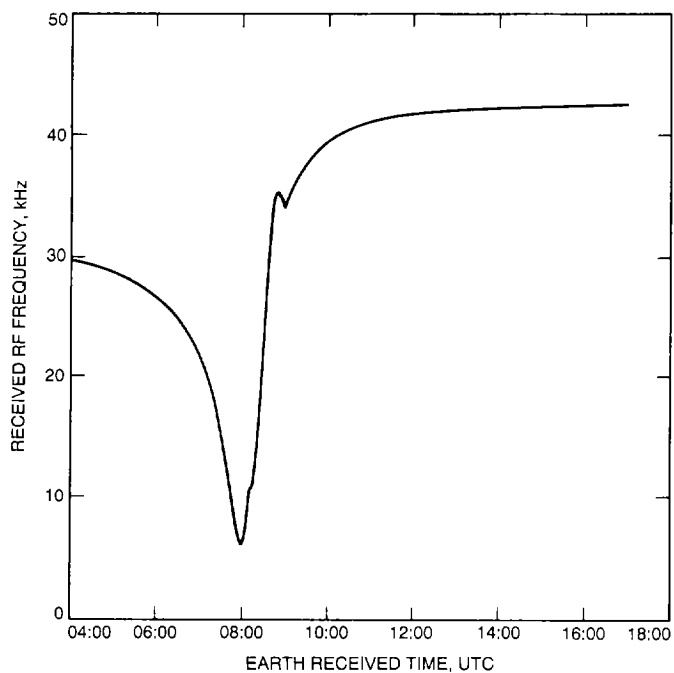
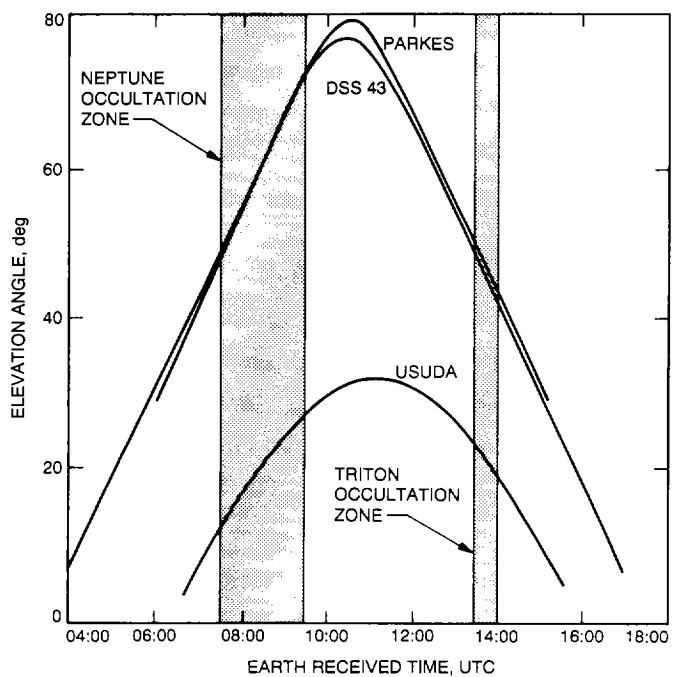Fig. 1. DSS 43 X-band downlink frequency at 8419 MHz.
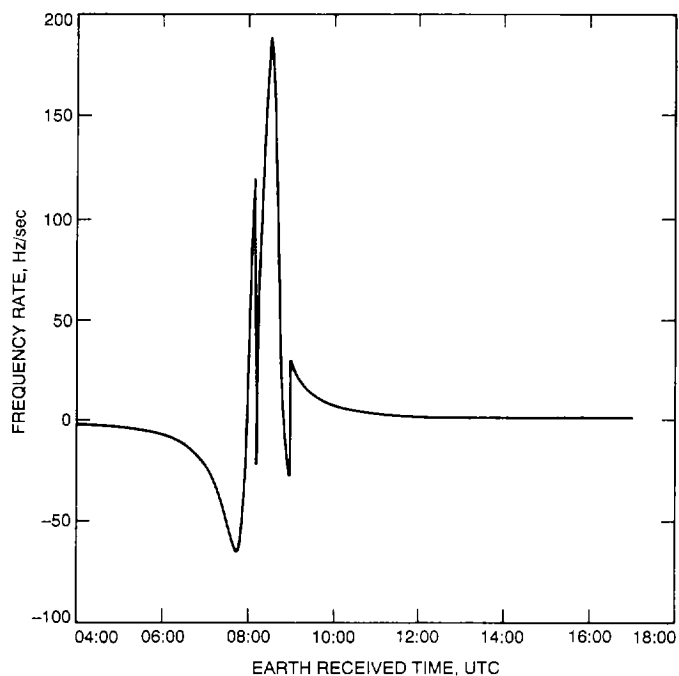

Fig. 3. DSS 43, Parkes, and Usuda elevation angles.
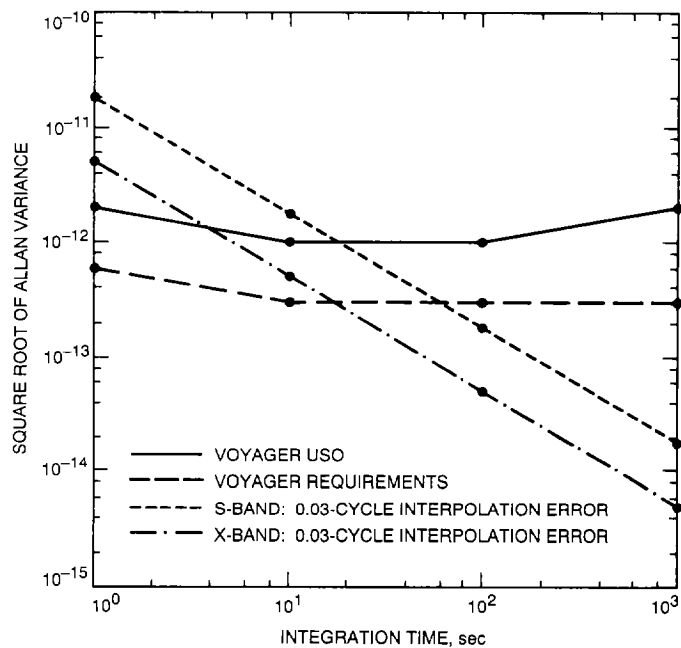

Fig. 2. DSS 43 X-band Doppler rates.
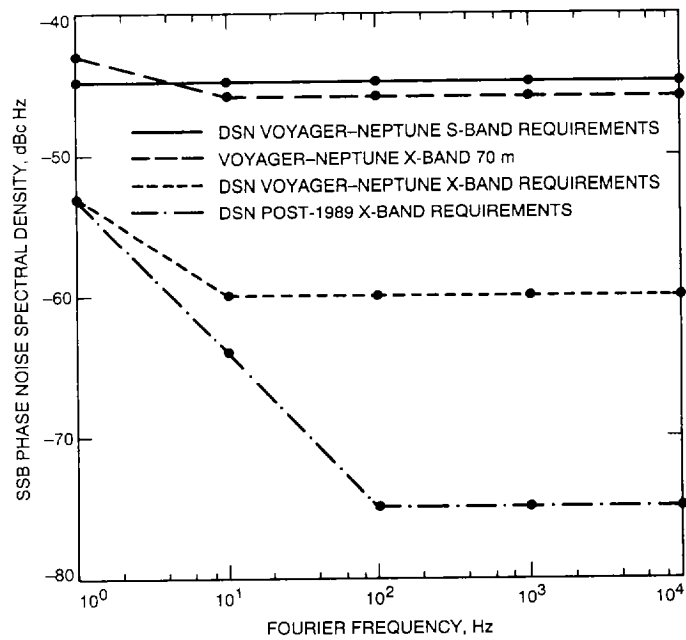

Fig. 4. Phase-stability performance.

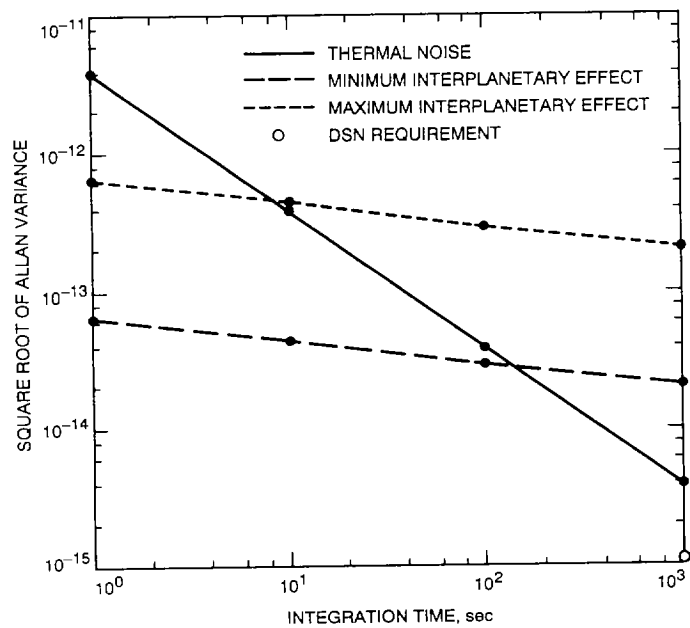**Fig. 5. Phase-noise performance.**

Fig. 6. Differential phase (S-3/11X) stability. This assumes a 30-dB·Hz SNR_0 and 1-Hz detection bandwidth. Interplanetary effects are derived from [10].